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FORCE ARMAMENT LAB EGLIN AFB FL L A ANKENY ET AL.
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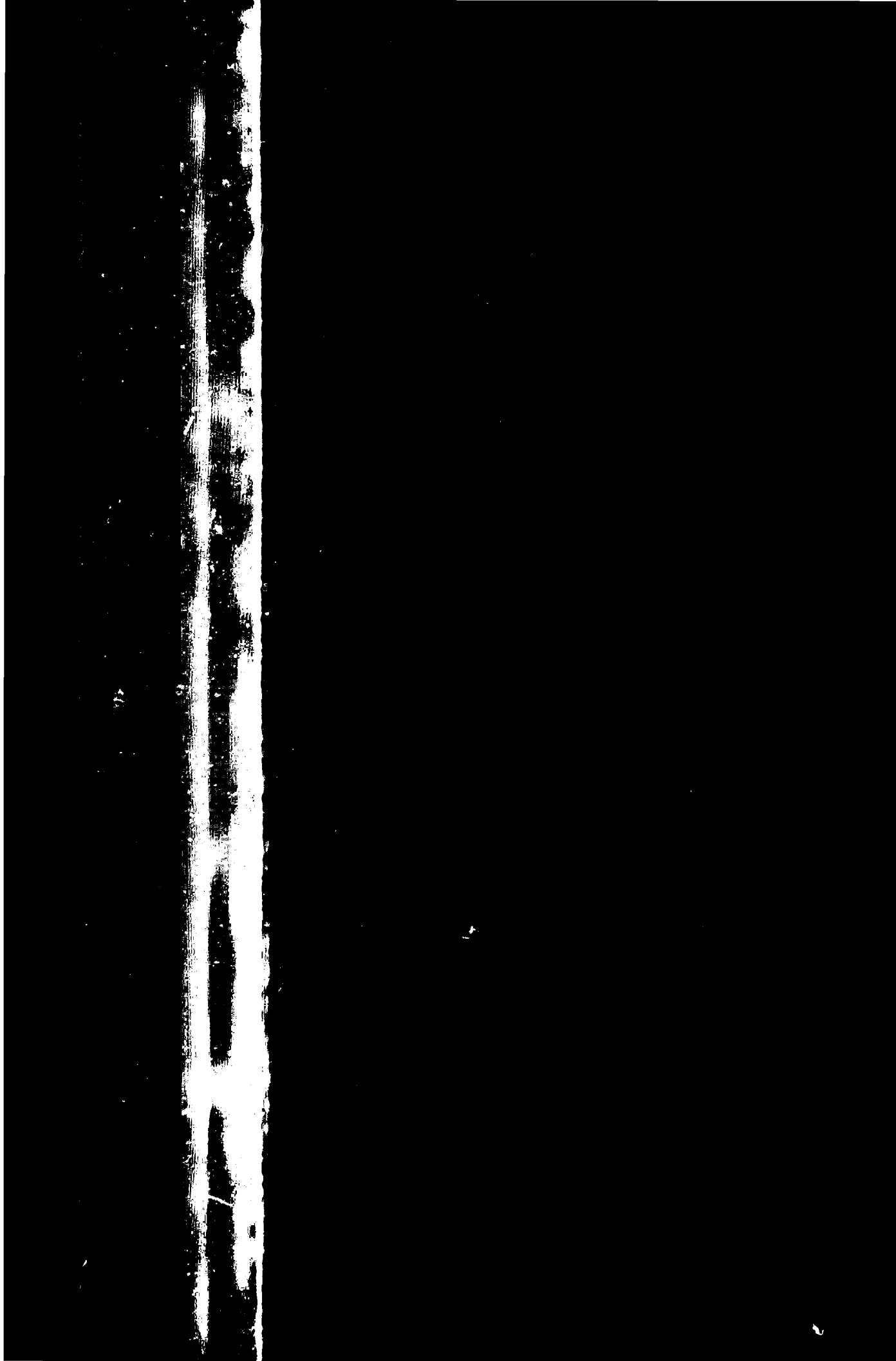
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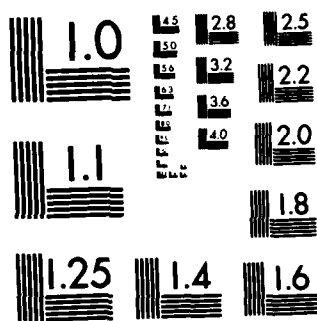
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On a Mathematical Structure for an Image Algebra

by

Lawrence A. Ankeney and H. Neal Urquhart

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The processing of images based on well-defined mathematical techniques has remained a subject of great interest for many years. In particular, mathematical theories associated with the processing, enhancement, analysis, and recognition of sensed imagery have received a significant amount of attention and effort as witnessed by the number of publications, organizations, and conferences devoted to this subject. The interest in this field of research is due to several factors, including (a) the wide-ranging fields of application (e.g., from biomedical and industrial uses to military applications), (b) the widespread availability of processing hardware (with increasing speeds and reliability, accompanied by decreasing costs), (c) the challenge of developing software that accomplishes tasks heretofore only accomplished by humans, and (d) the tantalizing applicability of rigorous, analytical methodologies which form the existing mathematical basis of present embryotic image processing theory (e.g., the formulation and development of image transforms, operators, and their mathematical properties). Consequently, the broad field of image processing theory and its application has rapidly evolved into one of today's most active and exciting areas of research.

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With one or two notable exceptions, there is no construct or theory that defines how to accomplish complex image processing tasks such as pattern recognition. Additionally, the extra spatial dimension, the highly correlated and nonstationary temporal statistical nature of most real world images, and the frequent use of multiple nonlinear image operations/transformations have quickly dispelled any useful application of classical signal detection and estimation theory and have driven algorithm development and evaluation to the lowly art of iterative trial and error. Worse yet, there is no standard notation or symbology that enables researchers to document their findings in a manner which is either unambiguous or easily comprehended by others.

Nevertheless, some attempts have been made to mathematically describe various collections of image processing methodologies into a rigorous mathematical framework, as exemplified by the work of Serra (6), Sternberg (7), and Miller (4). In spite of the efforts devoted to this discipline, the wide variety of existing methodologies associated with image processing have yet to be consolidated under one rigorous unifying mathematical structure. The primary motive for this circumstance may well be the way in which many methodologies have evolved historically. In general, most research programs have emphasized the practical or applications-oriented aspects of image processing. Thus, the development of a mathematical formalism within which the image can be processed in a well-defined, analytical, predictable fashion has been ignored. More specifically, image processing research has generally been characterized by one of several limitations or concerns: (a) development of software driven by a specific data base or task, (b) implementation of algebraic structures that emphasize a particular set of processing or algorithmic procedures, and (c)

use of approaches that are applications oriented or processor dependent. Thus, a general mathematical structure capable of allowing intelligent universal algorithmic formulation, evaluation, and documentation has yet to emerge from such diversified efforts.

In an attempt to overcome these limitations, the Air Force Armament Laboratory (AFATL) and the Defense Advanced Research Projects Agency (DARPA) have undertaken a two-phase, 33-month research program to develop a unifying image processing algebra. The first phase of the effort will begin by performing a mathematical analysis of existing image processing transforms, techniques, and methodologies. The initial goal of this phase is to identify a basic set of elemental operators that can be used to express a wide variety of existing image processing transforms. The participants in this program will demonstrate the capability and versatility of the identified operators by expressing a collection of typical image processing transforms in terms of the elemental operators. The second phase of the program will be devoted to the extension of the algebraic properties and to the identification of operational and transformational relationships and associated measurements.

If successful, the resulting image algebra will provide the image processing practitioner a set of rigorously defined mathematical notions which are capable of describing any two-dimensional image transform. Additionally, its algebraic properties will allow the user to mathematically translate image processing transforms into equivalent alternate formulations for ease in algorithm comparison and for a particular processor implementation. The resulting image algebra may ultimately enable image processing algorithms to be designed, developed,

evaluated, and documented using the unifying mathematical structure.

Since existing image processing transforms, techniques, and methodologies will serve as the starting point for the phase one analysis, the program will have a broad and rich mathematical environment from which to start. Within this mathematical environment there are several versions and even varieties of image algebras being developed. Naturally, some of these approaches are more mature than others and realistically some are more available than others.

For example, the morphological neighborhood image algebra of Serra is more mature than any of the other image algebras in terms of its mathematical foundation, formulation, and formalization. Also, it has matured as a consequence of its availability in the literature and resulting close scrutiny.

Mathematical morphology was born in France in 1964 and is currently gaining wide recognition in the broad areas of image processing and pattern recognition. Mathematical morphology permits the user to investigate the association between the forms or structures contained within the image under analysis and a shape considered significant by the researcher. This user-defined shape is referred to as a structuring element. The image is then analyzed by performing any one of many image transforms defined within mathematical morphology and then making the associated measurements. Naturally, the researcher has the responsibility of relating the resulting measurements to the solution of the original image analysis problem. These transforms use the structuring element as a probe and modify the image accordingly. Specifically, mathematical morphology has been used in the

analysis of biological images and is currently being applied to solve pattern recognition problems for machine vision systems. Also, mathematical morphology is achieving stature in the pattern recognition problems associated with autonomous guided weapons by providing a mathematical framework within which intelligent structured algorithm development can occur.

Although it does not have the extensive mathematical evolutionary credentials of Serra's image algebra, the morphological neighborhood image algebra of Sternberg does include major processing extensions, the most significant one being Sternberg's algebra of umbras. Umbra means shadow. Sternberg uses umbra to represent the volume of space that falls in the shadow of the surface of an image. A grey-valued image in two space can be considered as a binary image in three space. A point in the surface of a binary image in three space can be parameterized in terms of its altitude and its projection in two space.

The Neighborhood Transform Algebra (NTA) of Miller is not as mature and is not as available as either of Serra's or Sternberg's algebras. Miller's NTA has, however, been applied to three-dimensional pattern recognition problems for the Air Force. It is regretful, however realistically understandable, that, because of corporate proprietary claims, some of the more interesting application aspects of Miller's NTA are simply not available in the open literature.

Although the above algebras differ in mathematical maturity, there is a high degree of mathematical sameness in those areas that are common. Even though there is some difference in operational symbolism, transformational

definitions, and nomenclature, the common areas of these three algebras are fundamentally and functionally equivalent. The mathematical structure for these algebras has its basis in the works of Minkowski (5), Hadwiger (2), and Matheron (3).

Another approach to the development of an image algebra is taken by Ritter. His approach begins by defining a collection of basic image operators. Next, a collection of related definitions, properties, and relationships is formulated. This newly defined collection of basic image operators, together with related definitions, properties, and relationships, is then used by Ritter to express a collection of typical image processing transforms in terms of the basic operators. The significance of Ritter's work resides in the fact that both traditional image processing transforms and the more modern morphological transforms can be expressed in terms of a common set of basic operators.

Finally, a Universal Imaging Algebra is being initiated by Giardina (1). Giardina's approach to developing a Universal Imaging Algebra involves applying fuzzy set concepts to translate some image processing transforms into fuzzy transforms. These new fuzzy transforms are then applied in their defined manner. Giardina's fuzzy transforms operate on and generate values in the interval $[0, 1]$.

In conclusion, there is a critical need for the development of an image algebra. This algebra should be capable of describing arbitrary two-dimensional transforms and should provide not only a standard notation for documentation purposes, but should be based upon a unifying mathematical structure to provide clarifying insight to the design,

development, and optimization of image processing algorithm tasks. The work of several image algebra researchers illustrates several unique and promising technical approaches. The joint Air Force-DARPA program will evaluate competing image algebra concepts and fully explore the function and utility of the most promising techniques. With success, a unifying image algebra will move image processing algorithm development and evaluation further toward a theory of image analysis and algorithm formulation.

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